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ROBOTIC AND HUMAN-TENDED COLLABORATIVE DRILLING AUTOMATION FOR SUBSURFACE EXPLORATION

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Abstract

Robotic devices and humans interact with each other and themselves at differing levels of collective responsibility. Future space exploration requires both robotic and human components, in complementary roles. Future in-situ lunar/martian resource utilization and characterization, as well as the scientific search for life on Mars, will require access to the subsurface and hence drilling. Drilling on Earth is complex – an art form more than an engineering discipline. Human operators listen to and feel drill string vibrations coming from kilometers underground. Abundant mass and energy make it possible for terrestrial drilling to employ brute-force approaches to failure recovery and system performance issues. Space drilling will require intelligent and autonomous systems for robotic exploration and to support human exploration. This paper examines a modular, structured approach to human-robotic coordination, and shows how middleware and contingent plans are used in two examples that were field-tested at planetary-analog exploration sites in 2005.

Introduction

Humans and robots are each exploring – rather than defining a dichotomy between modes of exploration, they are exploring on Earth and in space in diverse groupings ranging from all-human teams to cooperating instruments and robots to humans amplified by automated helpers and applications. In space, the adaptability of humans is offset by the cost of life support and safety, while even highly-automated robotic explorers are stalled by small deviations from the expected, losing hours and days waiting for remote human troubleshooting. Humans can see and flag interesting features that are off-plan, while robots are prone to following orders even when a possible breakthrough lies just off of the path [1].

Eventual in-situ resource utilization (ISRU) will require deep drilling with probable human-tended operation of large-bore drills, but initial lunar subsurface exploration and near-term ISRU will be accomplished with lightweight, rover-deployable or standalone drills capable of penetrating a few tens of meters in depth. These lightweight exploration drills have a direct counterpart in terrestrial prospecting and ore-body location, and will be designed to operate either human-tended or automated. NASA and industry now are acquiring experience in developing and building low-mass automated planetary prototype drills to design and build a pre-flight lunar prototype targeted for 2011-12 flight opportunities. A successful system will include development of drilling hardware, and automated control software to operate it safely and effectively.

This includes control of the drilling hardware, state estimation of both the hardware and the lithography being drilled and state of the hole, and potentially planning and scheduling software suitable for uncertain situations (such as drilling).

NASA has invested a decade of research and engineering in studying ways to build on the relative strengths of both human and robotic explorers, in a more general sense. Combined human and robotic teams have been studied in the contexts of Space Station cooperative operations, such as Robonaut [2,3], or AERCam [4] for external or internal on-orbit operations in cooperation with human crew, either autonomously or teleoperated. Others have looked at the issues involved in amplifying human capabilities with automated robotic agents [5] in performing field geology tasks, either as software or as agents operating rover assistants or other devices.

Current rover missions are science-team driven, but constrained by both lightspeed delays and the periodic availability of deep space telemetry. Science team members plan the next 12-24 hours of operations, and then must wait until the next update interval to discover how much has been accomplished.

While rovers and their managing humans can use imaging to navigate around obstacles, drilling requires penetration of layers of unknown substrate. Terrestrial drilling in the oil and gas industry remains largely an art form, resistant to automation. Humans listen to audible frequency changes and feel changes in the mode shapes and vibrational patterns of a drill string as it lengthens and encounters new rock layers. Logging engineers analyze data from downhole sensors to identify useful trends and for tribology. On the Moon, eventual ISRU will require deep drilling with probable human-tended operation [1] of large-bore drills, but initial lunar subsurface exploration and near-term ISRU will be accomplished with lightweight, rover-deployable or standalone drills capable of penetrating a few tens of meters in depth. Mass and energy will be scarce. Early development and demonstration of automated drilling technologies is necessary – otherwise, no exploration mission designer will allow a drill on board their spacecraft.

This paper looks at issues of human and robotic coordination in exploration, formulates an approach, and discusses the relative success of that approach in the field tests of two projects in 2005.

Problem

An initial problem is merely to define the classes of interactions. Robots may be platforms, or effectors, or instruments, or software agents. Each of these may interact with others of the same kind or with other-kind individuals. Humans may work in remotely, in larger groups, in local, small groups or as individuals (either teleoperating or extra-vehicular).

One can imagine different exploration operations built buffet-style from several of these human and robotic types, varying the mix to address mission constraints and requirements. One software executive might supervise two local rovers and a drilling platform, as an example. Or a human in a spacesuit might be assisted by software agents (in the suit) and a rover (external). Or a remote science team might develop mission plans that a human in a local lunar/martian habitat executes through the teleoperation or supervision of several local robots. And doubtless many other combinations. But how can we integrate humans and robots flexibly? The problem is to develop a flexible but robust automation architecture capable of addressing such a variety of requirements -- but establishing patterns and protocols which ensure effective and efficient connectivity. The removal or failure of any given robotic element or communications link should not endanger humans nor stop mission operations.

Approach

In this paper, our approach is to decouple each human and robotic element from a need to know each other's internal state or data, and integrate them in a software-bus architecture. Each becomes a black-box in the view of others in a broad network. Hierarchies or peer networks may be defined by several layered or one software bus, respectively. Humans may be in remote teams, primary explorers (in extra-vehicular activity) or in a "daycare provider" model, supervising a number of semi-autonomous (toddler-like, in some sense) robots or software agents on an intervention-as-needed basis.

In internet commercial applications, similar requirements for modularity and data decoupling are addressed using middleware, adding a layer of disintermediation between functional producers and consumers of information. But commercial servers are not mass, power, or radiation-constrained unlike space computing. A full implementation of .NET or CORBA would consume more than the total available onboard processing power of current-generation rovers or drills.

But an open-standard subset is feasible and can be implemented. The MARTE Instrument Interface (MInI) is a simple and flexible communications package, based on a subset of the Common Object Request Brokering Architecture (CORBA) that was originally modified and descoped to ease the software development and integration process for the Mars Astrobiology Research and Technology Experiment (MARTE) [6,7]. MARTE is a complex, multi-national project that is developing and demonstrating an integrated drilling, sample handling, and science payload in order to simulate a Mars drilling mission. The MARTE project has many instruments and control systems being developed across a number of widely separated institutions in Spain, Texas, California, Oklahoma, and New York, as shown in Figure 1. All of these pieces needed to be developed independently at the home institutions, but yet come together during a short integration period and communicate across a number of different platforms. MInI was developed in order to facilitate this process [8].

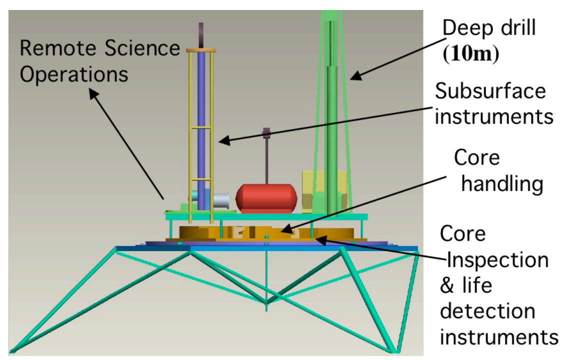

Figure 1. MARTE platform integrates instruments with a drill, sample handling robotics and remote science operations.

Another drilling project, the Drilling Automation for Mars Exploration (DAME) project [9] has leveraged the work done on MInI in order to facilitate communications between the elements in its own architecture. Figure 2 shows the overall DAME software architecture. The DAME architecture consists of an executive, MInI instrument dispatcher, drill server, diagnosis modules, diagnostic user interface, and drill controller. MARTE integrates 5 instruments, 1 drill, and a robotic core-handling effector under a platform-wide executive, is scenetended by a local human, and its executive receives plans and objectives twice a day from a remote science team.

The function of the contingent executive in DAME or MARTE is to send commands to the drill based on the state estimates it is receiving from the instruments, effectors or diagnostic modules. Developed originally for rover autonomous navigation and planning [10], it is purely a MInI client module, in that it sends commands and information requests to the other servers. Likewise, the diagnostic user interface is a client that allows a user to monitor the state of the system by requesting state estimates directly from the diagnostic modules. The diagnostic modules themselves continuously monitor the state of the system by receiving data from the drill server, and reasoning about this data in order to provide state estimates.

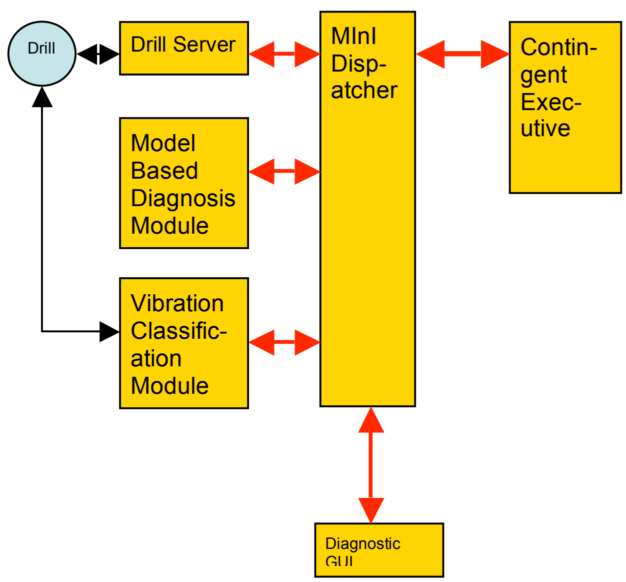

Figure 2. DAME diagnostic agents and executive.

The drill server receives data from the low level drill controller and provides this information to the other servers by either publishing the information (i.e., via the middleware), or answering direct queries. It also relays the commands from the executive to the low level drill control and device drivers.

The DAME diagnostic modules and drill server in Figure 2 are a departure from a typical client/server architecture, in that these modules must act as both clients and servers. The reason for this is that the vibration classification diagnostic module prefers to receive data from the drill server upon request, because it does periodic estimates based on occasional data samples.

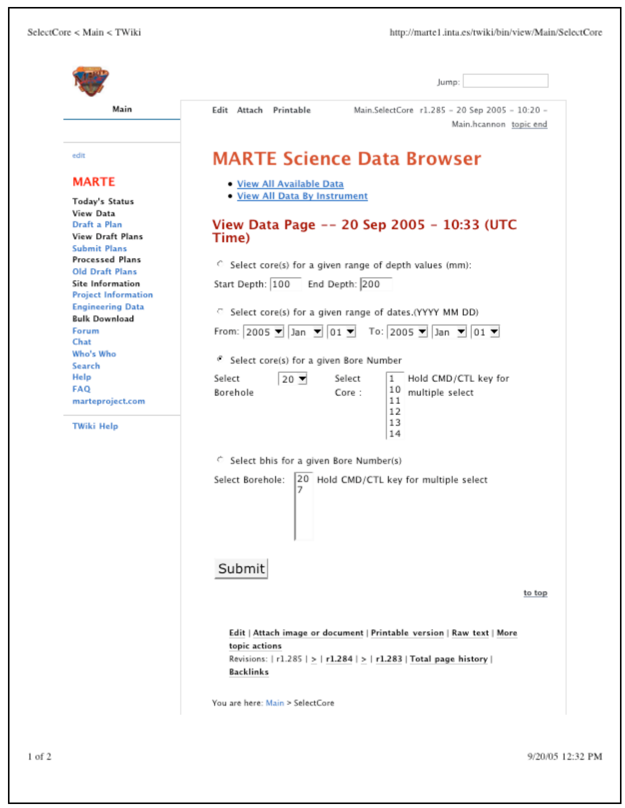

Figure 3. MARTE remote science top-level user interface, showing data retrieval and collaborative drilling-plan development options.

The model based diagnosis module continuously receives the data from the server in order to track the system with its internal model. MARTE implements a more-typical one-way client architecture. DAME includes the study and benchmarking of hybrid diagnostic techniques in drill diagnosis, as well as applying fuzzy learning methods to the structural dynamics of drilling systems.[11]

MARTE's remote science operations mimics how humans might control a robotic drill on Mars or other planetary bodies. As shown in the choices in Figure 3, a science team meets daily, considers the incoming uploads from the remote "spacecraft" and decides on a new plan – including subsampling of previous day's rock cores, which analyses to run, and how much deeper to drill that day given the degree of interest (or lack) in the current strata. Figure 4 shows the communications paths between mission operations and the fielded system, linking the human and robotic systems.

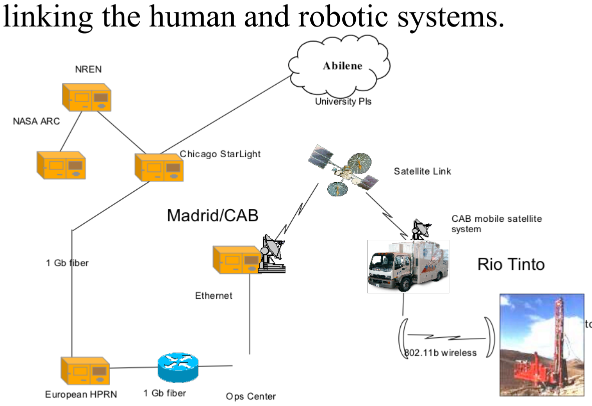

Figure 4. Remote operations links connecting humans and the fielded robotic systems and instruments.

Results

In daily field operations in September 2005, MARTE remote drilling relayed plans from a supervisory science team to the platform and its robotic drill and instruments. The humans on the science team did not need to know the platform-internal plans and sequences, and instruments and effectors were operated semi-autonomously and coordinated by the executive. Figure 5 shows the drilling platform, during these tests in Rio Tinto, Spain.

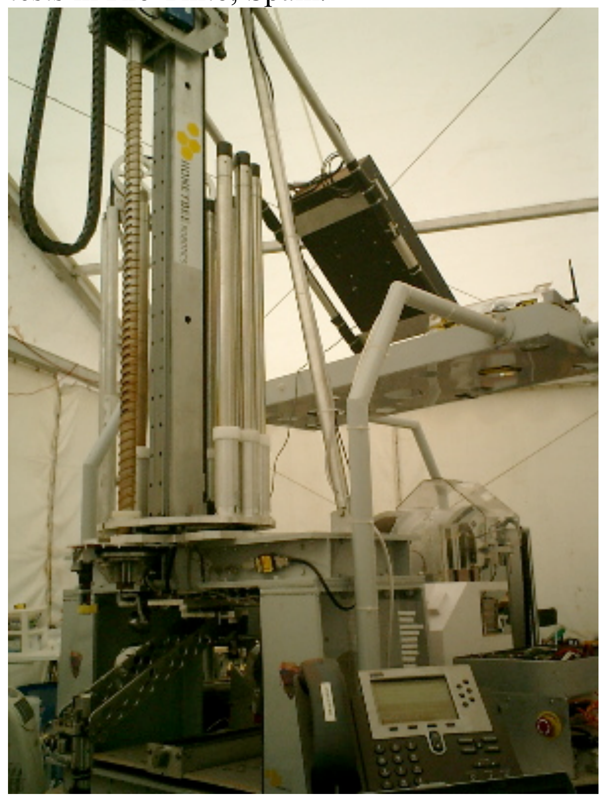

Figure 5. 2005 MARTE drilling tests at the Pena del Hierro analog site, near Rio Tinto, Spain.

A benefit of this modular operating approach was that the failure or maintenance of one given instrument did not require alterations to the software or controls of others, only small changes to the top-level executive plans. Instruments and effectors, as well as humans on the remote science team, did not have to know each other's internal state.

In the DAME field tests in July 2005 in Haughton Crater in the Canadian Arctic, in addition to testing mechanical drill operations, the DAME team integrated the Honeybee Robotics drill control software with the initial NASA-developed platform executive and ran simple drilling plans. DAME is intended to develop and test drill fault diagnosis and recovery, so the observe-only diagnostics and monitoring fielded in summer 2005 tests at Haughton will lead to the DAME software in control of drilling in the summer of 2006. The 2005 DAME tests, shown in Figure 6, used two diagnostic agents – one that used model-based reasoning from sensor values, the other a neural network that perceived the vibrational frequency and modal signatures of the drill shaft – which were successfully tested, independently detecting five fault states and reporting their findings to the executive.

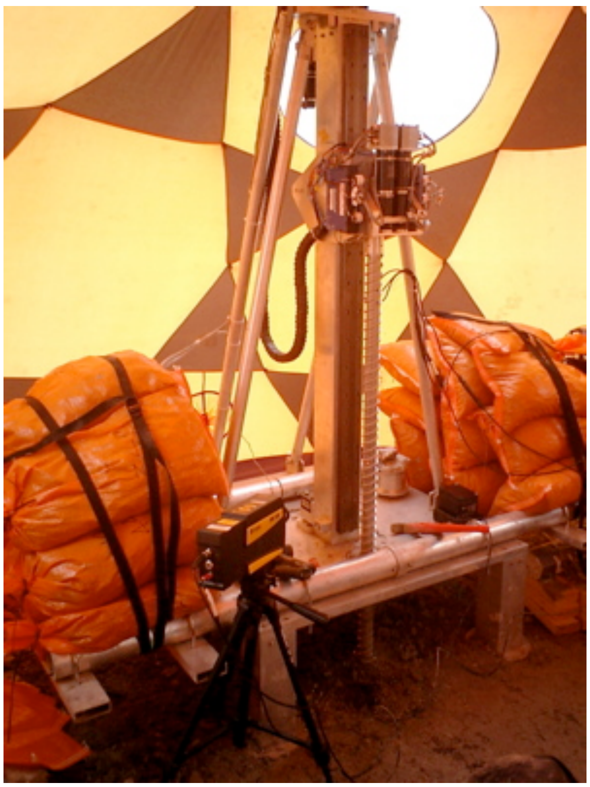

Figure 6. 2005 DAME drilling tests in the Canadian Arctic demonstrated autonomous fault diagnosis into mixed rock and ice layers at the Haughton Crater analog site.

Another result of this modular and middleware-based approach to integrating robotic and human components has been its ease of adaptation to other applications. For example, the new Construction and Resource Utilization Explorer (CRUX) project, which is developing a suite of robotic instruments and tools for surveying lunar regolith, has adapted MInI and this modular control and planning approach for CRUX core controls in just a few months since project start.

Conclusions

Given that humans on the Moon or Mars are unlikely to be able to spend protracted EVA periods at a given exploration site, both human-tended and robotic access to planetary surfaces and subsurfaces will require some degree of standalone, autonomous robotic exploration capability. Human-robotic coordination will be important, either between a robotic explorers and humans on Earth, or a human-tended drill and its visiting crew. The Mars Astrobiology Research and Technology Experiment (MARTE) is a current project that studies and simulates the remote science operations between an automated drill in Spain and a human remote science team. The Drilling Automation for Mars Exploration (DAME) project, by contrast, is developing and testing standalone automation at a lunar/martian impact crater analog site in Arctic Canada.

Modularity in software integration and scaled-down middleware has been very useful for integrating legacy instruments, robots, and humans in varying combinations, as well as facilitating rapid prototypes and quick testing of different mixes of instruments and/or robots. This has been developed and demonstrated and field-tested successfully with several planetary exploration prototypes. We have developed a flexible but robust automation architecture capable of addressing a variety of requirements for human and robotic collaboration in drilling projects.

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